Incorporating feasibility and collaboration into large-scale planning for regional recovery of coral reef fisheries

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ABSTRACT: Broad-scale overharvesting of fish is one of the major drivers of marine biodiversity loss and poverty, particularly in countries with high dependence on coral reefs. Given the heterogeneity of fishing effort and management success, and the scarcity of management resources, it is necessary to identify broad-scale locations for promoting successful fisheries management and conservation. Here, we assessed how fisheries management and conservation priorities in the Western Indian Ocean would change if the objectives were to (1) minimize lost fishing opportunity, (2) minimize the time for fish biomass to recover, (3) avoid locations of low management feasibility based on historical management outcomes, and (4) incorporate international collaboration to optimize the rate for achieving goals. When prioritizing for rapid recovery of fish biomass rather than minimizing lost fishing opportunity, we found that the area of priority management zones changed by over 60 % in some countries. When locations of low management feasibility were avoided, the recovery time of fish biomass across the region increased 4-fold. International collaborations prioritized management zones in remote, high biomass, and low fishing pressure reefs and reduced the recovery time of fish 5-fold compared to non-collaboration scenarios. Thus, many of these conservation objectives favored wealthy and sparsely populated over poorer and natural resource dependent countries. Consequently, this study shows how prioritization policies, incentives, decisions, and conflicts will produce highly variable outcomes and challenges for sustainability.

KEY WORDS: Africa · Conservation planning · Marine and fisheries policy · Marxan · Indian Ocean · Sustainable fisheries

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INTRODUCTION

Coral reef fisheries are harvested beyond sustainable levels in many regions, which is often linked to loss of biodiversity and ecosystem functions (Dulvy et al. 2004, Bellwood et al. 2011, McClanahan et al. 2011, Mora et al. 2011). Local fishery management, along with reduction of regional and global drivers of degradation, is imperative for recovery of reefs and sustainable fisheries (Hughes et al. 2010, Graham et al. 2013). Prioritizing locations for restrictions on fisheries or marine protected areas (MPAs) by utilizing

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marine spatial planning methods is expected to improve fisheries and the services provided by marine ecosystems (Fernandes et al. 2005, Gaines et al. 2010). However, planning less frequently considers the outcomes of different priorities, assumptions, incentives, decisions, and consequences of large-scale collaboration histories, instead aiming to minimize the adverse impacts of conservation plans on fisheries (Ban & Klein 2009, Metcalfe et al. 2015).

While fisheries policies and management actions propose to achieve sustainable fisheries, the lack of clear and scaled metrics of success has led to poor planning in many cases (Worm et al. 2009). One useful metric is reef fish biomass, because it is easily measured and is associated with predictable declines in ecological states, processes, and ecosystem services (McClanahan et al. 2011, Pereira et al. 2013, Karr et al. 2015, Mac-Neil et al. 2015). Therefore, reef biomass is an integrative metric that can be used for setting management objectives with clear ecological thresholds (McClanahan 2018). For example, in the Western Indian Ocean (WIO), maximum sustainable fisheries yield and ecological health occurs when total reef biomass is between 300 and 600 kg ha^{-1} (McClanahan et al. 2011). Conservation areas, where all ecological processes are maintained, should have a biomass of ~1150 kg ha^{-1} in the WIO (McClanahan et al. 2015). Consequently, biomass thresholds and recovery rates can inform spatial prioritization objectives (McClanahan et al. 2016).

Increasing agreement and compliance with management plans should be a primary objective when developing sustainable fisheries policies (MacNeil et al. 2015, McClanahan et al. 2016). Therefore, there is a need to consider how socioeconomic and political characteristics influence the likelihood of achieving strong compliance (hereafter referred to as 'management feasibility') (Mascia 2003, McClanahan et al. 2016). The factors influencing management feasibility are diverse, and include strength of governance (Ostrom 2007), perceptions of management legitimacy (McClanahan & Abunge 2016), and willingness of management entities to collaborate (Knight et al. 2010). While some maps of feasibility have been developed across a variety of spatial scales (O'Connor et al. 2003, Knight et al. 2010, Mills et al. 2013), it is rarely considered in spatial prioritization (Polasky 2008, Mills et al. 2013). By making feasibility a constraint in spatial prioritization, the risk of inappropriate placement and compliance failures is minimized.

International collaboration is also important in socio-politically complex regions where conflicts occur on borders and management resources are scarce, such as the WIO (Cordner 2010, Bueger 2013, Kark et al.

2015). Collaboration, when successful, has been shown to substantially reduce the cost and area required for managing terrestrial and marine environments (Kark et al. 2009, Mazor et al. 2013). Management costs and effectiveness vary across the WIO and collaboration has the potential to reduce shared costs to achieve desired outcomes, such as maintaining fish populations. Transboundary conservation, for example, has been identified as a regional priority between Kenya, Tanzania, and Mozambique to reap potential benefits of collaboration (Nairobi Convention 2015).

By explicitly incorporating management feasibility and international collaboration into management objectives, we built on previous spatial prioritizations using fish biomass recovery information (McClanahan et al. 2016). First, we assessed how using fish biomass recovery changed the spatial distribution of fishery management priority zones compared to the common zoning method of minimizing lost fishing opportunity. Second, we tested the influence of management feasibility on regional management priorities with a feasibility index using measures of fish biomass uncertainty, effectiveness of existing management, and estimates of collaboration potential between WIO countries. Finally, we explored potential socio-politically relevant scenarios of international collaboration to consider how collaboration can improve fish biomass recovery goals.

MATERIALS AND METHODS

The study area covered the mapped coral reefs in the large region of Kenya to South Africa, and east to the Maldives and Chagos. A previous study developed a 2.5 km^2 grid of fish biomass model based on a publicly available map (Reefs at Risk: www.wri.org/our-work/project/reefs-risk) and 7 predictor variables and their interactions (McClanahan et al. 2016). Variables were those known to influence the large-scale distributions of fish, and included strictness of management, compliance with management, the presence of fishing, distance to markets and market population, and 3 measures of sea surface temperature (Cinner et al. 2016). It is important to note that a limitation of this model is its inability to incorporate smaller scale local influences, such as benthic cover. While detailed benthic cover data would have been informative, data are only available for a small sub-section of the WIO (Maina et al. 2015), so could not be included. Time-to-recovery maps were developed using fish biomass recovery rates (kg yr^{-1}) to thresholds for sustainable fishing (450 kg ha^{-1}) and for conservation areas

(1150 kg ha^{-1}). McClanahan et al. (2011) based these thresholds on the fact that maximum sustained fishing yield in the WIO occurs between 300 and 600 kg ha^{-1} and selected the sustainable fishing threshold as the mid-range estimate for sustainable fishing production (450 kg ha^{-1}). They also used a conservation threshold of 1150 kg ha^{-1} because below this level is where the first measured changes in ecological processes (e.g. carnivory and herbivory) begin to appear. For full methodological details on fish biomass modeling and biomass thresholds, see McClanahan et al. (2016).

Spatial prioritization for reef fishery management

We used the conservation prioritization software Marxan with Zones (Watts et al. 2009) to identify priority areas for fisheries management. Marxan with Zones uses a simulated annealing algorithm to determine sets of sites that fulfill pre-determined quantitative targets for biodiversity features while minimizing cost, and also allows for the selection of different management zones (Watts et al. 2009), such as conservation zones or sustainable fishing areas. The cost values used in Marxan with Zones can reflect actual monetary costs (e.g. land purchase price), or any other value that is desirable to minimize (e.g. lost fishing opportunity). We used the 2.5 km^2 grid from the fish biomass model as a planning unit, and used the area of the World Conservation Monitoring Centre (WCMC) coral reef distribution (UNEP-WCMC et al. 2010) in each planning unit as a biodiversity feature. We explored questions using different prioritization objectives, but for all objectives we set targets (i.e. proportion of reef in a zone) to include 50% of reef area in sustainable fishing zones and 20% in conservation zones, while accounting for existing high compliance fishery closures (McClanahan et al. 2016). We conducted 10 Marxan with Zones runs of 100 repetitions for each objective, producing 10 'best solution' outputs for each objective. The 'best solution' output is the reserve system that performs best at reaching its feature targets with minimal cost. To map Marxan with Zones results, we considered a planning unit to be selected as a conservation or sustainable fishing zone if it was selected in 8 of the 10 'best solution' outputs. Using these base methods, we analyzed 3 spatial prioritization objectives — fishing opportunity baseline, time-to-recovery, and management feasibility — which differed only in the values used to be minimized by Marxan with Zones (see Table S1 in the Supplement at www.int-res.com/articles/suppl/m604 p211_supp.pdf for a summary of objectives).

Fishing opportunity baseline objective

Our baseline spatial prioritization objective used estimates of artisanal fishing landings as the value to be minimized in Marxan with Zones. Minimizing lost fishing opportunity is a common approach in spatial prioritization analyses (Klein et al. 2010, Grantham et al. 2013, Mazor et al. 2013), and we hereafter refer to this objective as the fishing opportunity baseline objective. Fish landing estimates were taken from Halpern et al. (2008), which modeled fish landings from national FAO small-scale fisheries statistics; the data are freely available (doi:10.5063/F19Z92TW). These data give approximate annual artisanal fishing catch at a 1 km^2 resolution. As our planning units were 2.5 km^2, we used the average artisanal fishing catch within each planning unit as the value to be minimized in Marxan with Zones. Because the artisanal fishing data did not cover remote islands and atolls, we assigned planning units without artisanal fishing data the lowest quartile value of artisanal fishing estimates for the region. Therefore, the Marxan with Zones algorithm ensured that conservation and sustainable fisheries zones contained at least 20 and 50% of coral reef in the WIO, respectively, while minimizing the amount of lost opportunity for artisanal fishing due to the placement of management zones.

Time-to-recovery objective

Our second spatial prioritization objective followed McClanahan et al. (2016) by using Marxan with Zones to minimize fish biomass recovery time (hereafter the time-to-recovery objective). Compared to the fishing opportunity baseline objective, this substitutes fish biomass recovery time for artisanal fishing catch as the value to be minimized. Thus, our time-to-recovery for the sustainable fishing zone reflects how long it takes for fish biomass to recover to 450 kg ha^{-1}. Similarly, the time-to-recovery value for the conservation zone reflects how long it would take for biomass to recover to 1150 kg ha^{-1}.

Management feasibility objective

To examine the impacts of incorporating management feasibility, we used the following equation to create a feasibility score (F) that represented the raw time-to-recovery values used in the fish biomass recovery objective, weighted by a measure of manage-

ment feasibility (hereafter the management feasibility objective). F was used as the value to be minimized in Marxan with Zones, and was calculated using the following equation (see Figs. S1 & S2 in the Supplement for maps of F values):

$$F_{i(i=1...n)} = T_i(E_i + C_1 + R_i) \qquad (1)$$

where T_i represents the time-to-recovery (in years) of coral reef in planning unit i, and n is the total number of planning units. E represents the percentage of successfully managed MPAs in a country, and was taken from Rocliffe et al. (2014) for all countries and territories except Bassas Da India, British Indian Ocean Territory, Glorioso, Ile Europa, Ile Tromelin, and the Maldives, which were assigned E from Reefs at Risk Revisited (Burke et al. 2011). These values were then normalized between 0 and 100 using a fuzzy logic linearly decreasing membership function. E was included because new management activities are likely to be more feasible in areas where current management practices are successful.

C represents the potential for collaboration between countries, and was calculated by normalizing country-level collaboration scores from Levin et al. (2018) between 0 and 100 using a fuzzy logic linearly decreasing membership function and spatially assigning these country scores to planning units. These collaboration scores were derived using linkages between nations based on biodiversity (number of shared species), trade (import/export value between countries), governance (number of shared environmental agreements), and spatial location (geographic relationship) (Levin et al. 2018). We used Thiessen polygons (Thiessen 1911) to determine the nearest exclusive economic zone (EEZ) boundary for each planning unit, and assigned planning units the collaboration score for the 2 countries that share boundaries (Fig. S3 in the Supplement). For example, a planning unit where the closest EEZ boundary is between Kenya and Tanzania would receive the C value for Kenya–Tanzania collaboration. Areas of high collaborative potential may be more feasible for management when considering cross-boundary collaboration, especially for reefs located between 2 countries or territories (Levin et al. 2018).

R_i represents a measure of model over-estimation of fish biomass recovery time for planning unit i, and is computed from the residuals of the biomass prediction model. To calculate R, we used the predicted biomass at upper and lower 95% confidence intervals (CI) from McClanahan et al. (2016) to calculate time-to-recovery. This allowed us to produce optimistic estimates of time-to-recovery (i.e. from using upper CI) and conservative estimates of time-to-recovery (i.e. from using lower CI). We then computed R as the ratio of conservative time-to-recovery estimates (lower CI) and optimistic time-to-recovery estimates (upper CI), from the mean predictions of biomass recovery time (taken from McClanahan et al. 2016). These values were then normalized between 0 and 100 using a fuzzy logic linearly decreasing membership function. Our feasibility metric penalizes areas where optimistic biomass predictions (upper CI) are further from mean predictions than conservative biomass predictions (lower CI), because modeled fish biomass in these areas is more likely to be overestimated than underestimated. We included variable R to penalize areas where biomass overestimation is more likely than underestimation, because if biomass is overestimated the actual time-to-recovery for that area will be longer than anticipated. In the reverse situation, time-to-recovery will be underestimated and management activities will be required for a shorter time than anticipated.

Cross-boundary collaboration scenarios

To investigate the role of cross-boundary collaboration in spatial management prioritization, we allocated planning units to countries or regions using EEZs (e.g. Kenya, Glorioso Islands). We compared 3 international collaboration scenarios, sensu Kark et al. (2009) and Mazor et al. (2013). These were (1) full collaboration scenario with all countries collaborating; (2) partial collaboration scenario, where countries that are currently part of conservation/environmental management agreements collaborate; and (3) no collaboration scenario, where each country acted in isolation. For the partial collaboration scenario we used 2 groups of collaborating countries: Kenya and Tanzania, who have identified transnational collaboration as a regional priority as per the recent convention of parties (COP8) of the Nairobi convention (Nairobi Convention 2015), and members of the Indian Ocean Commission (Comoros, Madagascar, Mauritius, Seychelles and Réunion; Commission de l'Océan Indien 2011).

Comparing prioritization objectives and collaboration scenarios

To compare management priorities under the (1) fishing opportunity baseline, (2) time-to-recovery, and (3) management feasibility objectives, we calcu-

lated the area of sustainable fishing and conservation zones under each objective within each country. We also compared the spatial arrangement of selected areas under each objective. Finally, we calculated the Fleiss' Kappa statistic (Fleiss 1971) to summarize the difference in selection frequency across all planning units, where 1 indicates that the combination of planning units selected is identical under each objective, and 0 indicates that all scenarios are distinct. To examine the role of international collaboration scenarios, we compared the area and spatial arrangement of priority areas in each country with respect to the 3 levels of collaboration, under both the time-to-recovery and feasibility objectives.

RESULTS

Comparison of objectives

Management priorities set under the time-to-recovery and management feasibility objectives differed markedly from the fishing opportunity baseline objective that aimed to minimize lost fishing opportunity within management zones. Conservation zones were 50% larger in the fishing opportunity baseline objective compared to the time-to-recovery objective, whereas the area of sustainable fishing zones was similar across all objectives (Table 1). The time required for fish biomass to recover in conservation zones was 13 times lower under the time-to-recovery objective than the fishing opportunity baseline, with similar reductions seen for sustainable fishing zones (Table 1). Average time-to-recovery increased 6-fold for conservation zones under the management feasibility objective compared to the time-to-recovery objective, but sustainable fishing zones had similar biomass recovery times (Table 1).

When comparing the time-to-recovery and management feasibility objectives to the lost fishing opportunity baseline objective, the area of management zones within individual countries differed by up to 51% for conservation zones (Fig. 1a) and 62% for sustainable fishing zones (Fig. 1b). For example, the Seychelles had 42% more area included in conservation zones under the time-to-recovery objective compared to the fishing opportunity baseline objective. Conversely, Mozambique had 15% less area included in sustainable fishing zones under the time-to-recovery objective compared to the fishing opportunity baseline objective (Fig. 1b). These results reflect the fact that Seychelles has high fish biomass levels and is thus a high priority under the time-to-recovery objective, whereas fish biomass in Mozambique is much lower due to high levels of fishing. Incorporating management feasibility also resulted in considerable differences with the time-to-recovery objective. For example, Madagascar had 15% more reef area included in sustainable fishing zones under the management feasibility objective compared to the time-to-recovery objective, while Tanzania had 18% less (Fig. 1b). A number of countries showed very small differences between all objectives, such as Kenya and Mauritius (Fig. 1a,b).

Broad priority areas for management zones remained similar under both the time-to-recovery and management feasibility objectives, with conservation priorities concentrated in the Seychelles, Maldives, and Chagos (Fig. 2). However, there were differences within countries for both the spatial arrangement and total area of management zones (Fig. 3). For example, reefs in the central Maldives were assigned a much higher priority under the time-to-recovery objective, whereas reefs in the north and south were high priorities under the management feasibility objective. Some areas of northern Madagascar became more important under the time-to-recovery objective (Fig. 3), despite Madagascar overall having 21% less reef area in sustainable fishing zones under this objective. Similar spatial differences were seen between the time-to-recovery objective and the fishing opportunity baseline, and between the management feasibility objective and the fishing opportunity baseline (Figs. S4 & S5 in the Supplement). When comparing across all objectives, the Fleiss' Kappa statistic was 0.25 and 0.47 for sustainable fishing and conservation zones respectively, indicating a low level of similarity between objectives (Table S2 in the Supplement).

Table 1. Average time-to-recovery (T_r) and number of planning units (PUs) selected in conservation and sustainable fishing zones identified under 3 different prioritization objectives

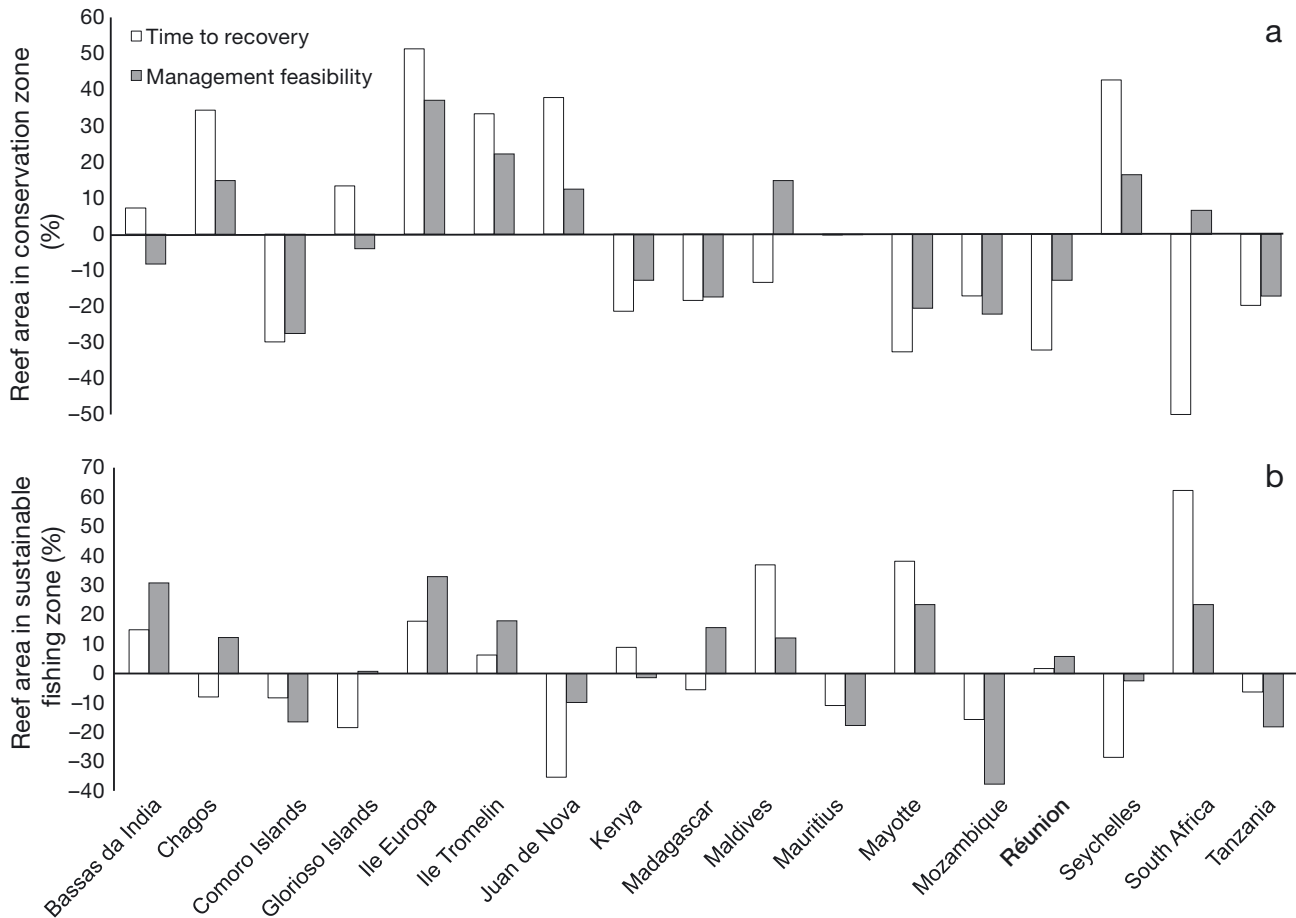| Prioritization objective	Conservation zones		Sustainable fishing zones	
	T_r (yr)	No. of PUs selected	T_r (yr)	No. of PUs selected
Time-to-recovery	0.7	1702	0.5	4574
Management feasibility	4.2	3371	0.7	3816
Fishing opportunity baseline	9.4	3436	2.0	4904

Fig. 1. Average difference from fishing opportunity baseline objective for (a) conservation zones and (b) sustainable fishing zones, expressed as reef area included in conservation and sustainable fishing zones, for priorities identified under the time-to-recovery objective (white) and the management feasibility objective (grey). Conservation zones and sustainable fishing zones contain 20 and 50% of total Western Indian Ocean (WIO) reef area, respectively. Values are the average of 10 'best solution' outputs from Marxan with Zones

Cross-boundary collaboration priorities

Cross-boundary collaboration reduced overall time-to-recovery and the area of management zones by redistributing management priorities toward island nations with high fish biomass, such as the Seychelles and Chagos. Results were similar under both time-to-recovery and management feasibility objectives, so here we report on the results of the time-to-recovery objective. Under a no collaboration scenario, the time required for fish biomass recovery was increased 5.4 times in conservation zones, and 3.4 times in sustainable fishing zones compared to the full collaboration scenario (Table 2). The partial collaboration scenario reduced recovery time by 37% in conservation zones, and over 150% for sustainable fishing zones (Table 2). A full collaboration scenario also required around 21% less area for conservation zones, and 38% less

for sustainable fishing zones compared to a scenario without collaboration (Table 2).

Collaboration substantially changed the location of management priorities, concentrating priorities in remote locations with high fish biomass (Fig. 4). For example, Chagos had 62% of its reef contained in conservation zones under a full collaboration scenario, but only 24% under a partial collaboration scenario (Fig. 4b). Conversely, Réunion had only 13% of its reef contained in sustainable fishing zones under full collaboration, but this rose to 51% under the no collaboration scenarios (Fig. 4a). In some nations, the effect of collaboration had contrasting effects for conservation zones and sustainable fishing zones. The Seychelles contained around 30% more reef in conservation zones under both collaboration scenarios, but around 20% less reef within sustainable fishing zones (Fig. 4).
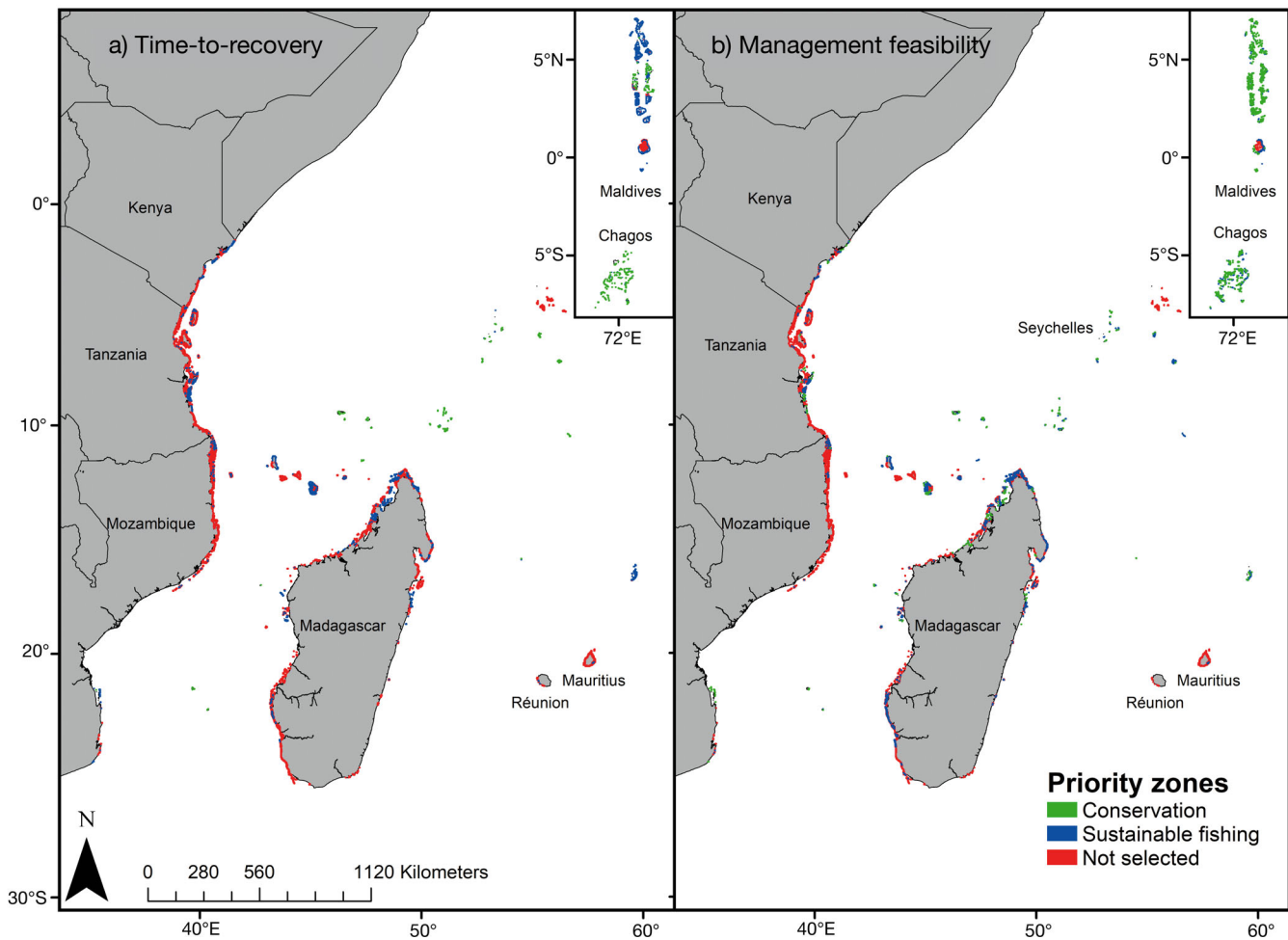
Fig. 2. Priority areas (selected in >80% of Marxan with Zones runs) for conservation and sustainable fishing zones from 10 'best solution' Marxan with Zones outputs: (a) priorities identified to minimize the time required for fish biomass recovery to sustainable fishing (450 kg ha^{-1}) and conservation (1150 kg ha^{-1}) thresholds (time-to-recovery objective). (b) Priorities identified to minimize time-to-recovery and avoid areas of low management feasibility (management feasibility objective). Each scenario contains 20% of the total reef area as conservation zones, and 50% as sustainable fishing zones. This figure is available in high resolution at www.int-res.com/articles/suppl/m604p211_Fig2.png

DISCUSSION

Incorporating management feasibility and fish biomass recovery into spatial prioritization considerably changed the spatial arrangement of priority locations compared to the baseline, where lost fishing opportunity was the main consideration. Furthermore, the time required for fish biomass to recover increased substantially when avoiding zoning locations of low management feasibility. These increases were attributable to management zones being shifted from infeasible high biomass reefs to lower biomass areas with greater feasibility. Consequently, incorporating management feasibility into spatial prioritizations can help avoid spending resources where effective management seems unlikely (Mills et al. 2013).

Clearly, managing fisheries for socio-economic goals such as food and income is important, but conservation may be challenging and expensive if feasibility is not addressed first (Hicks 2011, McClanahan & Abunge 2016).

Fishery closures or MPAs often face considerable opposition from fishers, and the imposition of MPAs or other fishery management policies, such as gear restrictions or catch quotas, is unlikely to succeed without broad consensus and community support (Jameson et al. 2002, Beger et al. 2004, McClanahan et al. 2005, FAO 2006, Kamat 2014). Providing information on the length of time required for management to meet demonstrable ecological targets and incorporating fish biomass recovery into management planning should increase knowledge and gain sup-
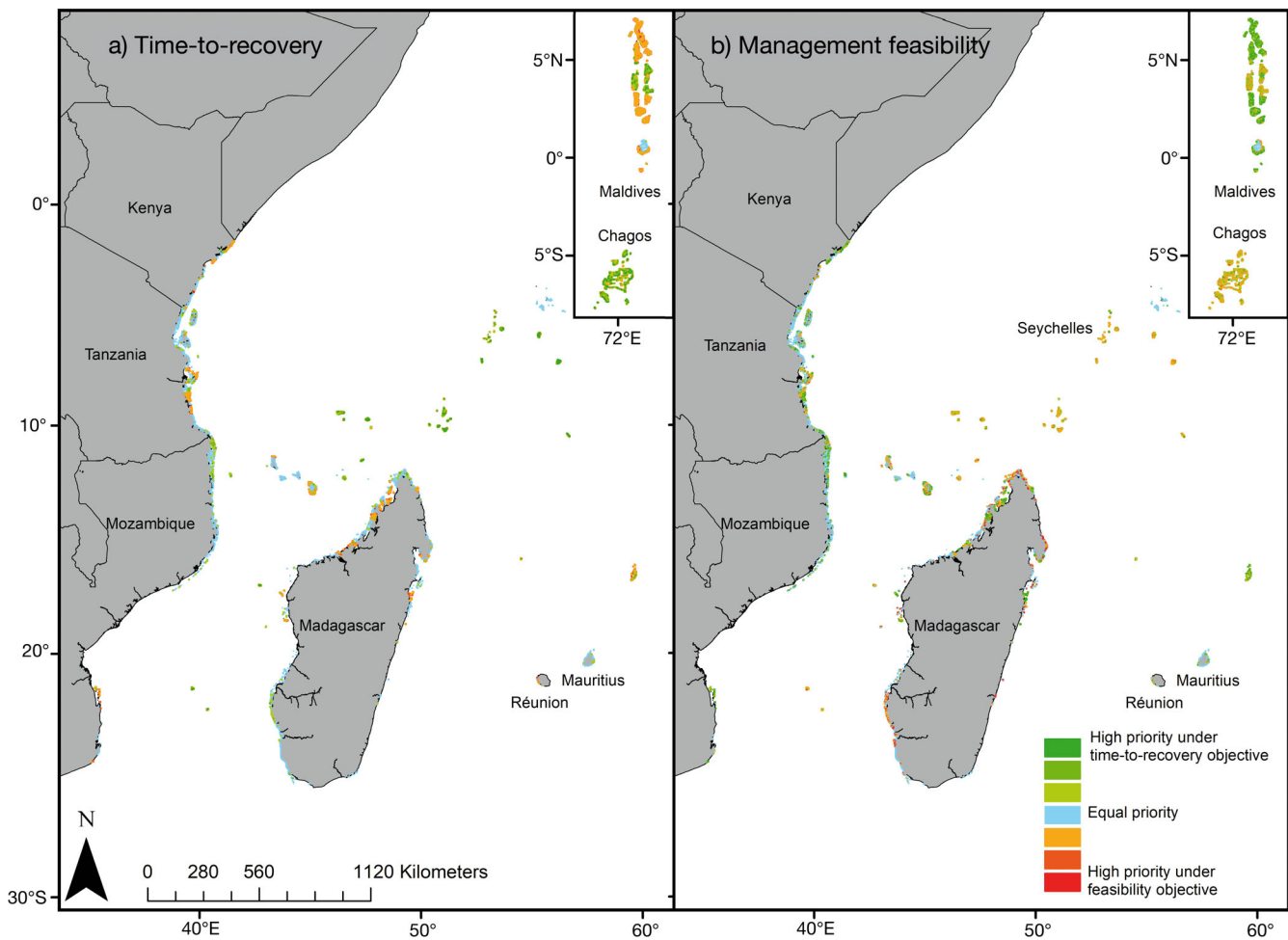
Fig. 3. Difference in planning unit selection frequency for (a) conservation zones, and (b) sustainable fishing zones under time-to-recovery and management feasibility objectives. Planning units are blue if they had equal selection frequencies under both objectives. This figure is available in high resolution at www.int-res.com/articles/suppl/m604p211_Fig3.png

Table 2. Average time-to-recovery (T_r) and number of planning units (PUs) selected in conservation and sustainable fishing zones identified under 3 different scenarios of international collaboration

International collaboration	Conservation zones		Sustainable fishing zones	
	T_r (yr)	No. of PUs selected	T_r (yr)	No. of PUs selected
Full	0.7	1702	0.5	4574
Partial	2.4	1632	0.7	4468
None	3.8	2128	1.7	7267

port from stakeholders. Where many people are highly dependent on coral reefs for food and income, such as the WIO (Donner & Potere 2007), stakeholder perceptions and participation are critical to avoiding compliance failures (Graham et al. 2007, Levy 2010, McClanahan 2010).

International collaborations decrease costs of conservation and fishery management efforts but result in management zones being asymmetrically distributed (Table 2, Fig. 4). Fully collaborative conservation plans lead to some countries being exempt from conservation zones (e.g. South Africa, Réunion), while others face additional management responsibilities (e.g. Seychelles). As such, the efficiencies gained by collaboration must be balanced with social equity considerations (Kark et al. 2009, 2015, Halpern et al. 2013). Other spatial prioritization analyses came to similar conclusions for the WIO (Maina et al. 2015, McClanahan et al. 2016) and other marine regions (Kark et al. 2009, Mazor et al. 2013, Beger et al. 2015). Consequently, any gains achieved through regional collaboration will also need to balance considerations of
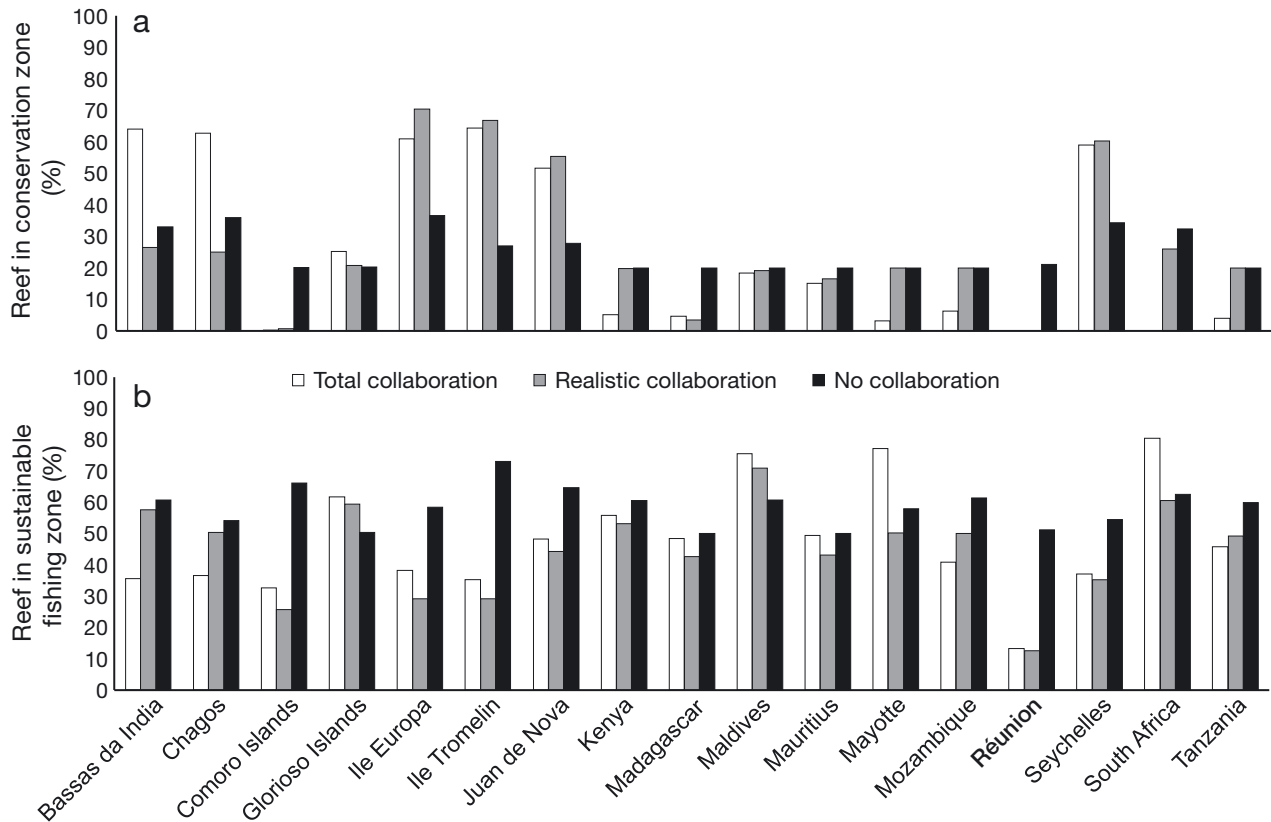
Fig. 4. Percentage of reef of each country contained in priority areas identified under 3 international collaboration scenarios, under time-to-recovery objective. Percentage of reef in each country contained in (a) conservation zones and (b) sustainable fishing zones. Values are the average of 10 'best solution' outputs from Marxan with Zones

sharing costs and responsibilities equitably. Among the many considerations of collaborative natural resource management are the broader suite of economic, political, and social barriers that influence implementation decisions (Sandwith et al. 2001).

The prioritization approach used here favors protecting high biomass areas, which essentially triages low biomass sites. Protecting high biomass is one of a number of goals of management and therefore alternative, and possibly a portfolio of, goals and zoning approaches should be considered. For example, Mc-Clanahan et al. (2016) proposed prioritizing the recovery of severely degraded reefs and the surrounding reefs. Another approach not mentioned here is to consider larval dispersal in spatial prioritizations to promote population recovery and persistence (Beger et al. 2010, 2015, Krueck et al. 2017, Álvarez-Romero et al. 2018, Magris et al. 2018). Depending on spatial scales, future work should consider using larval dispersal models (Treml et al. 2008, Kool et al. 2011) or genetic measures (Selkoe & Toonen 2011, Beger et al. 2014) to represent the larval connectivity within MPA networks. Given the empirical needs and computation

complexity of larval dispersal information, simpler approaches for informing MPA placement will be useful (e.g. minimizing distance between MPAs and fishing grounds; Krueck et al. 2017), although this does not discount the need for future research on incorporating larval dispersal into spatial prioritization, as the latter has been shown to influence priorities considerably (Magris et al. 2016). Including the costs of various management options, such as fisheries closures versus gear restrictions, has also been shown to substantially alter management priorities (Ban et al. 2011, Mc-Gowan et al. 2018). Furthermore, while total fish biomass is a useful holistic metric of reef function, it does not consider the different recovery rates of fish that are important for recovery of reef function (MacNeil et al. 2015, Martin et al. 2017). Consequently, future research priorities should include (1) combining spatial prioritization approaches to identify areas that overlap under multiple objectives (Allnutt et al. 2012), and (2) considering differential recovery rates and ecological functions of fish (McClanahan et al. 2015).

The data and estimates of management feasibility used here have a number of limitations. Firstly, we

used only one conservation feature — the area of coral reef per planning unit. While unlikely to change our main conclusions, incorporating better data on species′ distributions or biogeographical habitats, along with other conservation objectives (e.g. achieving representation) would likely alter the location of management priorities (Allnutt et al. 2012). Secondly, while our analyses were conducted at a broad spatial scale, the size of fisheries closures in the WIO is relatively small and compliance in these closures is mainly a local scale issue. Local scale studies which build upon our analysis could add important nuances to fisheries management plans. Thirdly, the management feasibility metric used here is dependent on national-level data and could be improved by incorporating more local scale assessments. Management feasibility is influenced by several factors not captured in our metric, including human values and perceptions, as well as economic, ecological, and technical issues (Salomon et al. 2011, Pascoe et al. 2014, Mc-Clanahan & Abunge 2016). Future studies should also consider the ability of local authorities to effectively enforce fishery closures, and the existence and competency of interacting governance networks (Nagendra & Ostrom 2012, Morrison 2017). Finally, perceptions of fishing restrictions and potential willingness to comply with regulations is known to vary considerably within and between WIO countries (Daw et al. 2012, McClanahan & Abunge 2016). Data on the perception of fishing restrictions by local communities could be used to assess the likelihood of compliance with fisheries closures/restrictions, thereby improving future management feasibility metrics.

There are also a number of limitations with the artisanal fishing data used in the fishing opportunity baseline objective, although they are the only high-resolution artisanal fishing data available across the entire WIO. These data use coastal population and distance-to-land to spatially model the small-scale distribution of national-scale catches (Halpern et al. 2008). This likely overestimates fishing catch on reefs near populated coastal ports, especially when fish landings at these ports reflect fishing effort from a large surrounding area. While artisanal fishing is notoriously difficult to estimate (Zeller et al. 2006, Halpern et al. 2008), incorporating local-scale data on landings at specific ports would help to avoid overestimation around densely populated areas. Furthermore, the artisanal fishing data does not discern between fisheries (e.g. reef fisheries, pelagic/offshore fisheries), and so reef fishing pressure is likely overestimated in places such as the Maldives, where fishers often target pelagic species (Hemmings et al.

2014). This will unduly reduce their selection by the Marxan with Zones objective function aiming to minimize cost. Consequently, incorporating data on catches of specific fish taxa (e.g. Watson 2017) could refine estimates of artisanal fishing to ensure they capture reef fishing effort specifically.

This study demonstrates how incorporating fish biomass recovery, management feasibility, and international collaboration affects fishery management priorities in the WIO — favoring remote and lightly fished regions. We also show that incorporating management feasibility redistributes priorities to wealthier nations or to those with histories of more effective management. Both outcomes result in an uneven distribution of management priorities, and may further burden people in poorer countries where effective fishery management is badly needed to promote food security. It is clear that for spatial prioritization analyses to be useful and incorporated into decision making, many possible values, incentives, scenarios, and metrics must be considered (Allnutt et al. 2012, McClanahan et al. 2016).

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